Biogeochemical patterns of created riparian wetlands: Eleventh-year results (2004)

William J. Mitsch, Li Zhang, Maria Hernandez, and Cassandra Tuttle

Olentangy River Wetland Research Park, School of Natural Resources, The Ohio State University

Introduction

As part of a long-term, large-scale experiment on self-design, two wetland basins at The Olentangy River Wetland Research Park (ORWRP) were set up as a planting experiment, i.e., one basin was planted in 1994 with 2400 individuals of macrophytes representing 13 species while a second wetland basin remained unplanted (Mitsch et al., 1998). The basins have gone through 11 growing seasons by the end of 2004 that have been characterized as follows:

• Year 1 (1994) – Wetland 1 (W1) was planted in May with Wetland 2 (W2) as unplanted control. Essentially both basins were algal ponds with few macrophytes.

• Year 2 (1995) – Wetland 1 plants developed, particularly around the perimeter to about 13% macrophyte cover in August, compared to essentially no macrophyte cover in Wetland 2. Floods in late June and early August brought in large carp with waters remaining turbid through much of the rest of the year.

• Year 3 (1996) – Wetland 1 continued to develop in vegetation cover with about 39% cover. Unplanted Wetland 2, particularly after spring drawdown in both wetlands to install sedimentation markers, developed to about 35% macrophyte cover by August, essentially catching up with the planted wetland within 3 growing seasons.

• Year 4 (1997) – Macrophyte growth continued to increase in both wetlands with about 54% cover in Wetland 1 and 58% cover in Wetland 2.

• Year 5 (1998) – Macrophyte cover was similar in the two basins but Wetland 2 began to be dominated by highly productive *Typha* spp. while Wetland 1 still had a wider diversity of cover and was not dominated by *Typha* spp. In other words, Wetland 1 plant cover was now more diverse.

• Year 6 (1999) – Wetland 2 was dominated by *Typha* while Wetland 1 continued to be dominated by 3-4 of the planted species.

• Year 7 (2000) – Similar to 1999 except muskrats developed in the winter of 2000 and began to have a dramatic effect on ecosystem function.

Table 1. Water quality sampling at Olentangy River Wetland site in 2004.

Sample frequency	# Sampling stations	Period in 2004	Equipment	Parameters measured
continuous	5	Feb-Nov	YSI 6600 sonde	temperature dissolved oxygen pH redox conductivity turbidity chlorophyll
twice daily	3 (inflow-W1; two outflows)	Jan-Dec	YSI 600xL sonde Hach turbidimeter (Lab)	temperature dissolved oxygen pH redox conductivity turbidity
weekly	7 (river; 1 inflow-W1; 2 middles; 2 outflows; swale)	Jan-Dec	YSI 600xL sonde Hach turbidimeter (Lab) LACHAT QuikChem IV (Lab) Shimadzu 5050A TOC analyzer (Lab)	temperature dissolved oxygen pH conductivity turbidity total phosphorus soluble reactive P TKN TOC $NO_3 + NO_2$

• Year 8 (2001)—Muskrat activity in the winter of 2000-2001 was extreme and vegetation cover was only a small percentage of what it was in previous years (see vegetation chapters in this report). This can be considered the year of maximum muskrat impact and vegetation cover was lower than any period since 1995. A continuous water quality sonde was installed in the Olentangy River on October 29, 2001.

Year 9 (2002)—Drawdown from April through June to allow plants to recover. Weekly water quality was not resumed after pumping began because of laboratory missing assignment, Both basins developed nice cover of *Schoenoplectus tabernaemontani*.

Year 10 (2003)—A pulsing experiment began in winter 2003 into both wetlands. Hydrologic pulses, usually of one-week duration, were administered to both wetland basins early in the months of February, March, April, May, June, and August. Continuous water quality probes were installed in the outflows of the two experimental wetlands on March 28, 2003 and in the inflow of Wetland 1 on November 2, 2003.

Year 11 (2004)—The pulsing experiment continued with pulses during the first week of February, March, April, May, and June. This year was the official pulsing year for a USDA-sponsored grant comparing results to 2005 non-pulsing conditions.

This study reports water quality results for the 11th year (2004) of operation of the experimental wetlands at the ORWRP. Other studies of the water quality of these wetlands are reported for Year 1 (Mitsch et al., 1995), Year 2 (Wehr and Mitsch, 1996; Mitsch and Nairn, 1996; Nairn and Mitsch, 1997), Year 3 (Mortensen et al., 1997; Mitsch and Carmichael, 1997; Nairn and Mitsch, 1997; Vorwerk and Mitsch, 1998), Year 4 (Mitsch and Montgomery, 1998; Spieles and Mitsch, 1998), and Years 5-10 (Mitsch et al., 1999, 2000, 2001, 2002, 2004; Mitsch and Zhang, 2003). Two undergraduate honors theses (Wehr, 1995; Vorwerk, 1997), two Master's theses (Harter, 1999; Dilley, 2003), two Master's theses from Europe (Mortensen and Lanzky, 1996; Kang, 1999) and four dissertations (Nairn, 1996; Spieles, 1998; Liptak, 2000; Ahn, 2001) have also investigated aspects of water quality at the site through 2004. Eight journal articles (Mitsch et al., 1998; Kang et al., 1998; Nairn and Mitsch, 2000; Spieles and Mitsch, 2000; Ahn and Mitsch, 2002; Anderson et al., 2002; Harter and Mitsch, 2003; Spieles and Mitsch, 2003) have been published on water quality of these experimental wetlands.

Methods

A summary of the water quality monitoring protocol for the two experimental wetlands in 2004 is shown in Table 1. Weekly water sampling, instituted in late April 1994 continued through 2004. Samples were taken at 7 stations in 2004 as in previous years. One 1000 ml sample was collected at each of the 7 sites. Water samples were taken to laboratories in the Heffner Wetland Research and Education Building where subsamples were filtered and frozen for later measurement of soluble reactive phosphorus. Unfiltered samples were preserved with concentrated H_2SO_4 (0.5 mL/100 mL sample) and frozen for later analysis of total phosphorus, nitrate+nitrite (NO_3+NO_2), TKN, and occasionally ammonia-ntrogen. A raw sample is also stored for TOC analysis. Sample preparation and preservation is usually completed within 48 hours of original collection.

Two-per-day water sampling, also initiated in 1994, continued through 2004 by the staff and students of the Olentangy River Wetland Research Park at Ohio State University. Inflow of Wetland 1 (determined after several studies to represent the inflow to both basins) and the outflows of Wetland 1 and Wetland 2 were monitored for temperature, dissolved oxygen, pH, conductivity, and redox with a YSI probe. Instruments were calibrated and checked for battery power frequently. Each time a 100-ml Nalgene bottle was used to take a sample for later measurement of turbidity in the lab at each of the three stations.

Sample Analysis

Standard Methods for the Examination of Water and Wastewater, 20th Edition (APHA, 1998) and EPA Methods for Chemical Analysis of Water and Wastes (USEPA, 1983) were followed. Total phosphorus, soluble reactive phosphorus, TKN, and nitrate+nitrite are analyzed on a quarterly or more frequent basis on a Lachat QuikChem IV automated system and Lachat methods (USEPA, 1983). Both total phosphorus and soluble reactive phosphorus methods employed the ascorbic acid and a molybdate color reagent method. Total phosphorus and TKN samples are first digested in a block digestor by adding 5 ml of a digestion solution made up of H_2SO_4 and K_2SO_4 to 20 ml of sample and exposing the samples to a heated environment for 1 hour at 160°C and continued digestion for 1.5 hr at 380°C. Nitrate+nitrate, run on the Lachat QuikChem IV automated system, used the cadmium reduction method. TKN, after digestion, is estimated by the salicylate and hypochlorite colorimetric method. TOC (total organic carbon) is estimated by a TOC analyzer (Shimadzu 5050A).

Results and Discussion

2004 Results and 11-Year Comparisons

Water quality results for 2003 weekly and two-per-day sampling are summarized in Table 2 while percent change through the wetlands and statistical significance are summarized in Table 3. A comparison of percent change in water quality for each of the 6 basic water quality indices for the entire 11-year period that the experimental wetlands have been in operation is given in Figure 1. A similar 10-year illustration is given for total phosphorus (Figure 2), nitrate+nirate-nitrogen (Figure 3), and soluble reactive phosphorus (SRP, Figure 4).

In 2004 there were increases in water temperature, dissolved oxygen, and pH and decreases in redox potential

Table 2. Summary of water quality measurements at Olentangy River experimental wetlands, 1996 through 2003. Two -per-day sampling refers to dawn-dusk sampling done almost every day that water is flowing. Numbers are average ± std. error (# of samples).

Parameter	Year	Olent. River	Inflow	Middle-W1	Middle-W2	Outflow-W1	Outflow-W2	Swale
Total P, μg-P/L	1996	185±15 (40)	191±18 (30)	85±11 (33)	77±9 (34)	68±8 (34)	64±9 (35)	62±9 (33)
	1997	149±16 (46)	146±17 (45)	99±7(39)	113±13 (38)	125±20 (41)	120±12 (43)	94±7 (44)
	1998	244±28 (47)	186±16 (46)	129±15 (47)	133±14 (47)	98±10 (47)	98±11 (47)	31±7 (47)
	1999	194±35 (48)	126±11 (44)	99±11 (43)	138±22 (41)	92±17 (44)	76±12 (45)	70±9 (45)
	2000	159±19 (49)	138±12 (48)	137±30 (41)	148±32 (40)	72±16 (46)	90±19 (47)	86 ±14 (46)
	2001	122±7 (43)	112±6 (42)	86±8 (38)	87±8 (36)	69±7 (41)	83±7 (43)	80±9 (40)
	2003	150±21 (37)	121±16 (35)	103±25 (24)	67±15 (22)	137±24 (35)	130±17 (37)	120±18 (36)
	2004	179±22 (54)	170±19 (48)	126±9 (43)	130±10 (40)	149±12 (49)	130±10 (47)	151±17 (51)
SRP, μg-P/L	1996	58±8 (38)	70±11(29)	19±4 (33)	16±4 (33)	8±1 (33)	9±2 (33)	9±2 (32)
	1997	50±6 (48)	67±12 (47)	23±3 (40)	25±3 (39)	26±3 (37)	23±3 (40)	37±13 (39)
	1998	89±11 (47)	82±10 (46)	45±9 (47)	45±9 (47)	27±6 (47)	31±7 (47)	31±7(47)
	1999	97±10 (47)	94±10 (43)	46± 8 (45)	33±6 (44)	27±4 (47)	24±4 (46)	23±4 (48)
	2000	83 ±9 (46)	82±9 (46)	27±4 (39)	27±4 (40)	19±4 (45)	27±5 (46)	31±6 (44)
	2001	67±9 (42)	60±8 (41)	38±6 (34)	22±3 (33)	23±5 (36)	25±6(37)	35±8 (36)
	2004	24±4 (54)	21±3 (49)	15±2 (43)	13±2 (43)	10±1 (49)	11±2 (50)	10±2 (48)
$NO_3 + NO_2$, mg-N/L	1996	4.60±0.41 (38)	4.42±0.42 (29)	3.08±0.38(34)	2.89±0.32(34)	2.97±0.40(34)	3.30±0.38(34)	3.19±0.47(31)
	1997	4.89±0.97 (48)	4.23±0.75 (47)	2.92±0.62 (39)	3.02±0.69 (39)	3.51±0.71 (42)	3.55±0.71 (42)	3.45±0.71 (44)
	1998	2.79±0.39 (47)	2.72±36 (46)	2.06 ±0.35 (47)	2.02 ±0.33 (47)	1.83±0.32 (47)	1.67±0.34 (47)	1.82±0.33 (45)
	1999	1.94±0.24 (47)	1.91±0.24 (44)	1.51±0.29 (42)	1.46±0.25 (44)	1.33±0.28 (45)	1.28±0.24 (45)	1.20±0.23 (47)
	2000	4.74±0.63 (49)	4.35±0.48 (48)	3.63±0.55 (41)	2.93±0.44 (42)	2.85±0.62 (45)	2.42±0.34 (46)	2.68±0.62 (43)
	2001	3.24±0.36 (42)	3.32±0.33(41)	2.42±0.37 (36)	2.26±0.38 (36)	2.14±0.34 (40)	2.56±0.37 (42)	2.41±0.32 (40)
	2003	3.10±0.30 (47)	4.06±0.33 (38)	2.32±0.29 (37)	2.03±0.30 (37)	2.39±0.34 (46)	2.28±0.32 (47)	2.12±0.28 (49)
	2004	2.27±0.25 (43)	2.38±0.30 (40)	2.14±0.31 (33)	2.22±0.31 (34)	1.71±0.17 (41)	1.69±0.18 (42)	1.89±0.21 (37)
TKN, mg-N/L	2004	0.62±0.05 (51)	0.57±0.04 (48)	0.75±0.05 (40)	0.71±0.05 (41)	0.79±0.06 (50)	0.93±0.15 (50)	0.73±0.05 (50)
TOC, mg-C/L	2004	6.9±0.7 (56)	6.5±0.8 (51)	5.9±0.6 (44)	5.7±0.6 (42)	7.0±0.8 (53)	6.9±0.7 (50)	7.2±0.9 (52)
Turbidity, NTU [1]	1996		35±3 (319)			21±2 (404)	20±2 (407)	
	1997		28±2 (453)			26±2 (426)	27±2 (447)	
	1998		25±2 (446)			16±1 (459)	16±1 (462)	
	1999		25±2(493)			19±1 (524)	20±1 (521)	
	2000		29±2 (436)			17±1 (442)	19±1 (449)	
	2001		17±1 (359)			17±1 (358)	18±1 (370)	
	2002*		22±3 (80)			29±2 (77)	30±2 (77)	
	2003		23±2 (154)			28±3 (139)	22±2 (146)	
	2004		31±2 (324)			37±2 (325)	35±2 (313)	
D.O., mg/L [1]	1996		9.69±0.19 (278)			10.55±0.21(336)	10.48±0.18(338)	
	1997		9.90±0.2 (454)			11.38±0.28 (412)	11.32±0.29 (430)	
	1998		9.40±0.14 (430)			11.98±0.26 (433)	11.66±0.25 (436)	
	1999		8.70±0.15 (463)			9.12±0.24 (486)	8.59±0.21 (489)	
	2000		9.96±0.18 (417)			10.81±0.24 (432)	9.46±0.21 (431)	
	2001		10.23±0.19 (353)			11.29±0.28 (353)	11.07±0.28 (362)	
	2002		10.72±0.33 (157)			11.07±0.43 (139)	10.82±0.39 (151)	
	2003		10.34±0.22 (184)			10.72±0.33 (180)	10.50±0.33 (194)	
	2004		10.2±0.2 (326)			12.3±0.3 (321)	13.1±0.4 (317)	
Temp, °C [1]	1996		14.9±0.5 (302)			15.5±0.4 (373)	15.7±0.4 (373)	
	1997		13.2 ±0.4 (476)			13.7±0.4 (443)	13.7±0.4 (464)	
	1998		14.6±0.4 (456)			15.0±0.4 (471)	15.1±0.4 (475)	
	1999		14.9±0.4 (488)			14.8±0.4 (512)	14.6±0.4 (509)	
	2000		13.6±0.4 (478)			14.5±0.4 (487)	14.3±0.4 (486)	
	2001		14.0±0.4 (413)			14.7±0.5 (402)	14.9±0.4 (411)	
	2002		11.8±0.8 (159)			11.3±0.8 (141)	12.1±0.8 (153)	
	2003		11.8±0.5 (215)			12.6±0.6 (199)	13.1±0.6 (217)	
	2004		13.8±0.4 (345)			15.1±0.5 (342)	15.7±0.5 (338)	
Cond., μS/cm [1]	1996		535±6 (282)			452±5(349)	454±5(350)	
	1997		621±7 (401)			576±7 (364)	593±7 (385)	
	1998		539±6 (450)			487±5 (462)	502±6 (467)	
	1999		550±8 (488)			527±8 (513)	533±8 (512)	
	2000		454±5 (479)			421±4 (485)	441±5 (486)	

continued

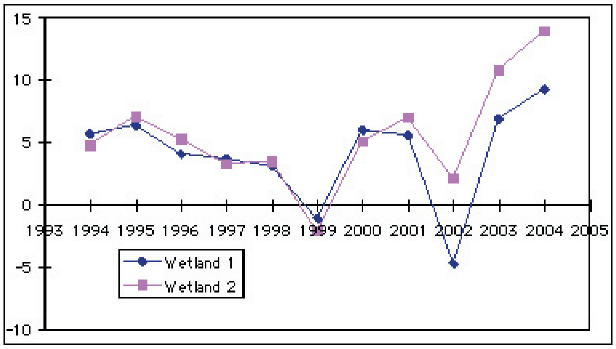
	2001	568±9 (410)	519±7 (400)	536±7 (410)
	2002	651±11 (159)	631±10 (139)	631±12 (152)
	2003	610±15 (215)	542±17 (193)	531±15 (218)
	2004	552±7 (335)	498±8 (315)	478±9 (317)
pH [1]	1996	7.91±0.02(300)	8.17±0.03(367)	8.19±0.03(368)
	1997	7.94±0.03 (443)	8.24±0.04 (412)	8.20±0.04 (431)
	1998	8.18±0.04 (365)	8.47±0.04 (374)	8.38±0.04 (375)
	1999	7.74±0.02 (480)	7.87±0.03 (502)	7.80±0.02 (502)
	2000	7.73±0.01 (425)	7.93±0.02 (438)	7.76±0.02 (433)
	2001	7.94±0.02 (412)	8.33±0.04 (402)	8.20±0.02 (411)
	2002	7.90±0.05 (148)	8.14±0.05 (128)	7.98±0.05 (136)
	2003	7.74±0.05 (194)	8.05±0.05 (181)	8.05±0.04 (203)
	2004	7.67±0.03 (345)	8.04±0.05 (342)	8.10±0.04 (337)
Redox, mV[1]	1996	394±4(213)	387±3(263)	384±3(265)
	1997	433±3 (338)	433±3 (352)	430±4 (377)
	1998	333±6 (440)	309±6 (450)	307±6 (456)
	1999	302±7 (436)	283±7 (460)	281±7 (457)
	2000	289±2 (376)	274±2 (386)	283±2 (383)
	2001	233±6 (263)	235±5 (234)	236±5 (242)
	2002	177±8 (81)	165±9 (75)	166±9 (80)
	2003	277±5 (203)	261±6 (184)	254±5 (207)
	2004	158±8 (337)	143±8 (330)	143±7 (327)

[1] two-per-day sampling
* winter data only

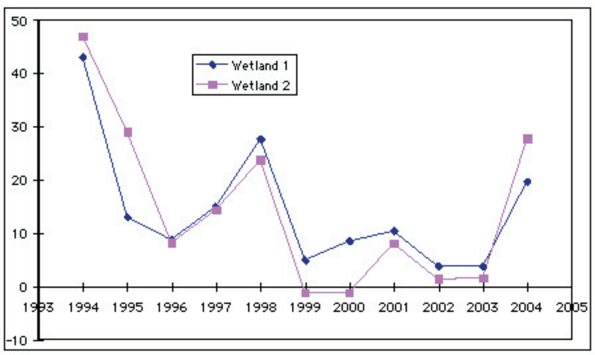
Table 3. Water quality changes from inflow to outflow within and between the experimental wetlands, and statistical significance, 1999-2004. W1 = planted wetland; W2 = unplanted wetland; In = inflow; Out = outflow; nd = no significant difference at $\alpha = 0.05$

Parameter and year	% change W1 (+ = increase, - = decrease)	% change W2	Paired t-test, p-value: In v. Out W1	In v. Out W2	Out W1 v. Out W2
Temp 99	-1.1	-2.1	nd	nd	0.0070
Temp 00	+6.0	+5.1	0.0000	0.0134	0.0000
Temp 01	+5.6	+7.0	0.0000	0.0000	nd
Temp 02	-3.9	+2.9	0.267	0.0067	0.0314
Temp 03	+6.9	+10.8	0.0119	0.0003	nd
Temp 04	+9.2	+13.9	0.0000	0.0000	nd
DO 99	+4.9	-1.2	nd	0.0438	0.0001
DO 00	+8.5	-5.0	0.0000	0.0010	0.0000
DO 01	+10.4	+8.1	0.0000	0.0000	nd
DO 02	+3.3	+1.0	nd	nd	nd
DO 03	+3.7	+1.6	0.0084	nd	nd
DO 04	+19.6	+27.7	0.0000	0.0023	0.0068
Cond 99	-4.2	-3.1	0.0002	nd	0.0014
Cond00	-7.2	-2.9	0.0000	0.0000	0.0000
Cond01	-8.5	-5.5	0.0000	0.0000	0.0001
Cond 02	-3.0	-3.1	nd	nd	nd
Cond 03	-11.2	-13.1	0.0000	0.0000	nd
Cond 04	-9.9	-13.5	0.0000	0.0000	nd
pH 99	+ 1.7	+0.7	0.0001	0.0020	0.0001
pH 00	+2.7	+0.4	0.0000	0.0040	0.0000
pH01	+4.9	+3.2	0.0000	0.0000	0.0000
pH 02	+3.0	+1.1	0.0000	0.0000	0.0004
pH 03	+4.0	+4.1	0.0000	0.0000	nd
pH 04	+4.8	+5.5	0.0000	0.0000	0.0021
Redox 99	-6.3	-6.8	0.0001	0.0001	nd[1]
Redox 00	-5.1	-2.3	0.0000	0.0000	0.0000
Redox01	1.0	1.5	0.0000	0.0000	0.0000
Redox 02	-6.9	-6.5	0.0365	0.0602	nd
Redox 03	-6.0	-8.6	0.0207	0.0000	0.033
Redox 04	-9.2	-9.2	0.0000	0.0000	nd
Turbidity 99	-24.3	-18.2	0.0001	0.0070	0.0044
Turbidity 00	-42.7	-35.2	0.0000	0.0000	0.02751
Turbidity01	-0.6	8.2	nd	nd	nd
Turbidity 02	+29.2	+31.9	0.0085	0.0177	nd
Turbidity 03	+25.4	-5.1	nd	nd	nd
Turbidity 04	+21.5	+13.2	nd	nd	0.0034
Total P 99	-27	-40	0.0128	0.0001	nd
Total P 00	-47	-34	0.0000	0.0184	nd
Total P 01	-39	-26	0.0000	0.0001	0.0115
Total P 03	-13	-7	nd	nd	nd
Total P 04	-12	-24	nd	0.0064	nd
SRP 99	-71	-75	0.0001	0.0001	nd
SRP 00	-77	-67	0.0000	0.0000	nd
SRP 01	-62	-59	0.0000	0.0000	nd
SRP 04	-51	-47	0.0002	0.0005	nd
$NO_3 + NO_2$ 99	-30	-33	0.0001	0.0001	nd
$NO_3 + NO_2$ 00	-34	-44	0.0004	0.0000	nd
$NO_3 + NO_2$ 01	-35	-23	0.0001	0.0086	nd
$NO_3 + NO_2$ 03	-41	-44	0.0002	0.0000	nd
$NO_3 + NO_2$ 04	-28	-29	0.0073	0.0066	nd
TKN 04	+38	+63	0.0038	0.0243	nd
TOC 04	+8	+7	nd	nd	nd

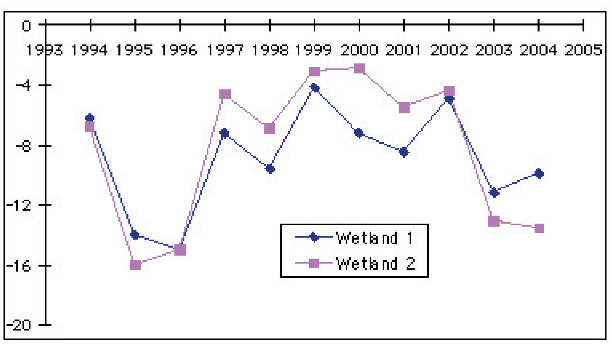
a) Water Temperature



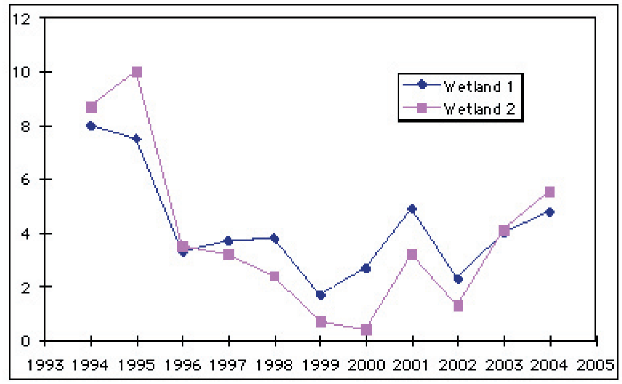
b) Dissolved Oxygen



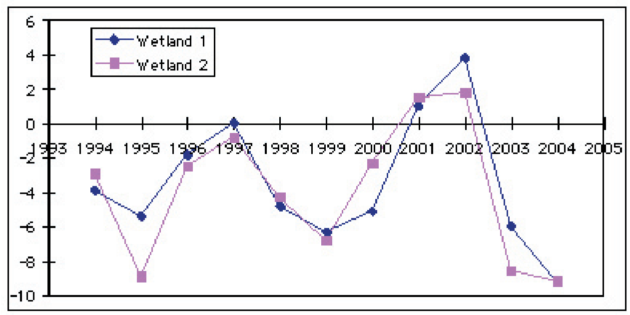
c) Conductivity



d) pH



e) Redox Potential



f) Turbidity

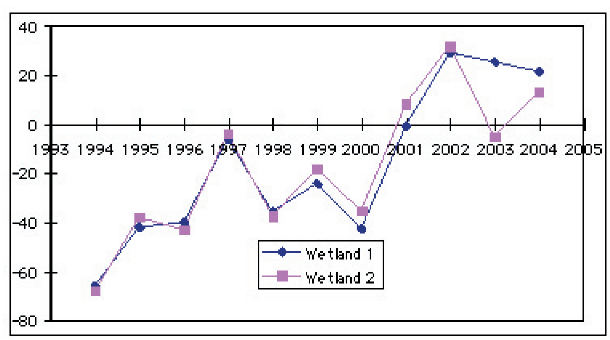


Figure 1. Changes in water quality, 1994 - 2004, in experimental wetland basins. Values are expressed as percent change from inflow to outlfow.

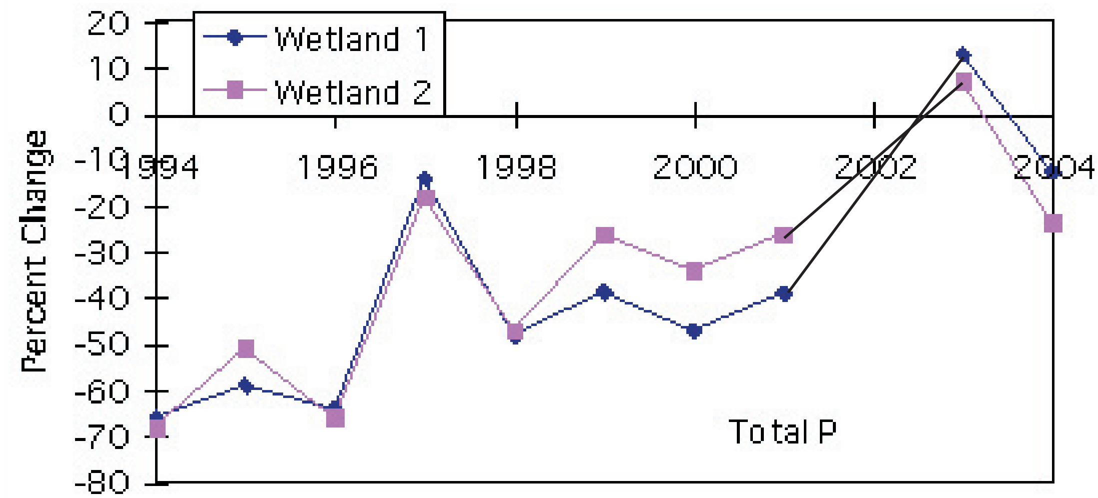


Figure 2. Changes in total phosphorus for 1994-2004 in experimental wetland basins. Values are expressed as percent change from inflow to outlfow. No data were collected in 2002.

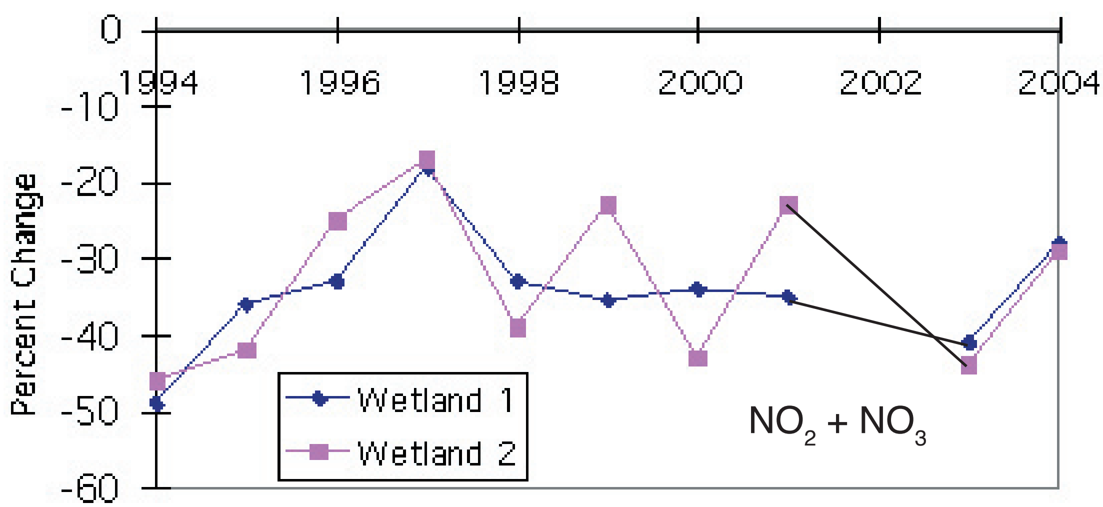


Figure 3. Changes in nitrate+nitrite-nitrogen for 1994-2004 in experimental wetland basins. Values are expressed as percent change from inflow to outlfow. No data were collected in 2002.

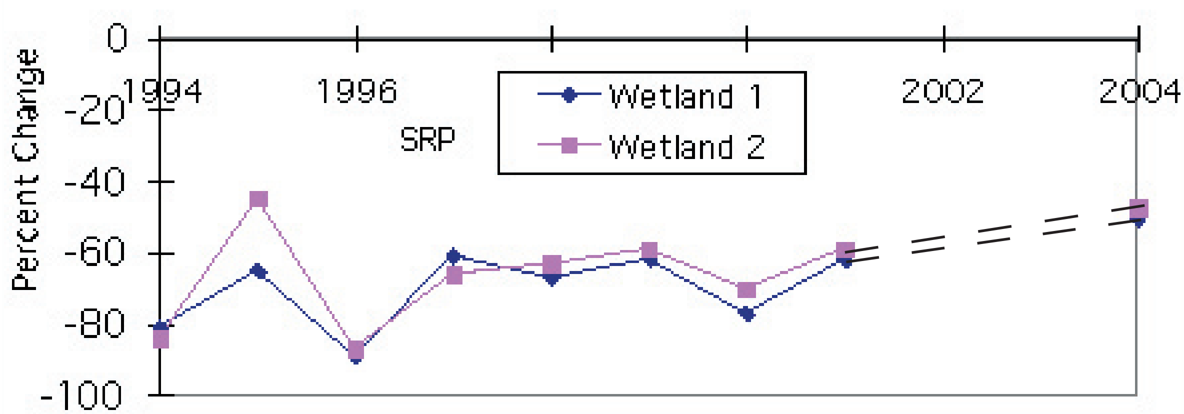


Figure 4. Changes in soluble reactive phosphorus (SRP) for 1994-2004 in experimental wetland basins. Values are expressed as percent change from inflow to outlfow. No data are reported for 2002 or 2003.

and conductivity through both wetlands (Table 3). There were no significant differences between the two wetlands for 8 of the 11 water quality parameters; there was no difference in 7 of 8 measured parameters in 2003. Dissolved oxygen, pH and turbidity were statistically different in the outflows of the two wetlands in 2004. In the previous year (2003) only redox potential was different between the two wetlands.

The wetlands continued to show a pattern started in 2003 of retaining less phosphorus (Figure 2). In 2004, inflow total phosphorus concentration averaged 170 μg-P L^{-1} while outflows were 149 and 130 μg-P L^{-1} for Wetlands 1 and 2 respectively. The wetlands continued to retain nitrate-nitrogen with a 28% decrease in Wetland 1 and a 29% decrease in Wetland 2 (Figure 3). Soluble reactive phosphorus continued its consistent pattern of decreasing significantly through both wetlands: 51 and 47% in Wetland 1 and 2 respectively (Figure 4) All of these water quality measurements include both flood pulse and steady flow conditions.

Pulsing Conditions

The year 2004 represented the second year in which hydrologic pulsing was purposefully applied to the expermental wetlands to determine the effects of flood pulsing on ecosystem function. During pulsing conditions, the only significant change in nutrient water quality from inflow to outflow was in Wetland 2 which retained 26% of total phosphorus (Table 4). During non-pulsing periods over the first half of the year, Wetland 2 showed signficant (α = 0.05) decreases in total P, SRP, and nitrate-nitrogen and significant increases in TKN (Table 4). Wetland 1 showed only a significant decrease in nitrate-nitrogen during that period. Results of pulsing v. non-pulsing will be more interesting when 2004 data are compared to non-pulsing data from 2005.

References

Ahn, C. 2001. Ecological engineering of wetlands with a recycled coal combustion product. Ph.D. dissertation, Environmental Science Graduate Program, The Ohio State University, Columbus.

Ahn, C. and W.J. Mitsch. 2002. Scaling considerations of mesocosm wetlands in simulating large created freshwater marshes. Ecological Engineering 18: 327-342.

American Public Health Association. 1998. Standard Methods for the Analysis of Wastewater, 20th ed., APHA, Washington, DC.

Anderson, K.L., K.A. Wheeler, J.A. Robinson, and O. H. Tuovinen. 2002. Atrazine mineralizaation potential in two wetlands. Water Research 36: 4785-4794.

Dilley, M. 2003. Atrazine fate and transport in a created flow-through emergent marsh: An examination of key processes. Master's Thesis, Environmental Science Graduate Program, The Ohio State University, 111 pp.

Harter, S.K. 1999. Patterns of short-term sedimentation in a freshwater created marsh. Master's Thesis, School of Natural Resources, The Ohio State University, 134 pp.

Table 4. Nutrient retention during pulsing and non-pulsing periods in experimental wetlands in 2004.

Wetland 1	River	inflow	Outflow W 1	Outflow W2	Swale	% reduction W1	% reduction W2	% reduction swale
PULSING CONDITIONS (Jan-June)								
Flow, gpm		800±120 (16) W1						
		826±123 (16) W2						
Total P, μg-P L^{-1}	198±29	206±19	169±20	153±17	168±14	18	*26	18
SRP, μg-P/L	28±8	27±8	16±3	19±3	17±4	39	30	36
NO_2+NO_3, mg-N L^{-1}	2.86±0.44	3.28±0.69	2.59±0.27	2.67±0.24	2.81±0.32	21	19	14
TKN, mg-N L^{-1}	0.64±0.08	0.64±0.80	0.65±0.06	0.64±0.05	0.64±0.05	-3	0	-1
TOC, mg-C L^{-1}	9.5±1.7	8.6±1.8	8.7±2.1	8.4±1.2	7.5±1.3	-10	-6	6
BETWEEN PULSING CONDITIONS (Jan-June)								
Flow, gpm		145±15 (19) W1						
		144±15 (19) W2						
Total P, μg-P L^{-1}	173±25	163±23	149±20	134±16	148±10	8	*18	9
SRP, μg-P L^{-1}	26±10	16±3	9±2	9±2	8±2	42	*42	47
NO_2+NO_3, mg-N L^{-1}	2.73±0.38	2.42±0.26	1.61±0.17	1.61±0.18	1.43±0.21	*33	*34	*41
TKN, mg-N L^{-1}	0.50±0.08	0.51±0.07	0.69±0.09	0.93±0.14	0.80±0.11	-34	*-81	*-55
TOC, mg-C L^{-1}	7.9±1.1	8.4±1.0	9.9±1.1	8.4±1.2	8.2±0.9	-18	0	3

* significant difference at α = 0.05

Harter, S.K. and W.J. Mitsch. 2003. Patterns of short-term sedimentation in a freshwater created marsh. Journal of Environmental Quality. Journal of Environmental Quality 32: 325-334.

Kang, H. 1999. The significance of enzyme activities in wetland biogeochemistry. Ph.D. thesis, University of Wales, Bangor, UK.

Kang, H., C. Freeman, D. Lee and W.J. Mitsch. 1998. Enzyme activities in constructed wetlands: Implication for water quality amelioration. Hydrobiologia 368: 231-235.

Liptak, M. 2000. Primary productivity and phosphorus dynamics in experimental created marshes. Ph.D. dissertation, Environmental Science Graduate Program, The Ohio State University, Columbus.

Mitsch, W.J., R.W. Nairn, X. Wu and A. Wehr. 1995. Water quality changes in Olentangy River water caused by the experimental wetlands at the Olentangy River Wetlands Research Park—first year results. In: Mitsch, W.J. and X. Wu (eds.) Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1994, Columbus, OH. pp. 51-61.

Mitsch, W.J. and R.W. Nairn. 1996. Nitrogen and phosphorus retention by the Olentangy River experimental wetlands, 1994-95. In: Mitsch, W.J. (ed.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1995, Columbus, OH. pp. 91-102.

Mitsch, W.J. and L. M. Carmichael. 1997. Water quality and nutrient removal patterns of created riparian wetlands: Third year results and a 3-year summary. In: Mitsch, W.J. (ed.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1996, Columbus, OH. pp. 127-138.

Mitsch, W.J. and H. Montgomery, 1998. Water quality and nutrient removal patterns of created riparian wetlands: Fourth year results. In: Mitsch, W.J. and V. Bouchard (eds.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1998. Columbus, OH, pp. 89-95.

Mitsch, W.J., X. Wu, R.W. Nairn, P.E. Weihe, N. Wang, R. Deal and C.E. Boucher. 1998. Creating and restoring wetlands: A whole-ecosystem experiment in self-design. BioScience 48: 1019-1030.

Mitsch, W.J., N. Wang, V. Bouchard, M. Ford and K. Mohler. 1999. Biochemical and nutrient removal patterns of created riparian wetlands: Fifth-year results. In: Mitsch, W.J. and V. Bouchard (eds.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1998. Columbus, OH, pp. 79-85.

Mitsch, W.J., V. Bouchard, L. Zhang, and M. Hunter. 2000. Biochemical and nutrient removal patterns of created riparian wetlands: Sixth-year results. In: Mitsch, W.J. and L. Zhang (eds.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1999. Columbus, OH, pp. 83-90.

Mitsch, W.J., L. Zhang, and M. Hunter. 2001. Biochemical and nutrient removal patterns of created riparian wetlands: Seventh-year results. In: Mitsch, W.J. and L. Zhang (eds.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 2000. Columbus, OH, pp. 29-34.

Mitsch, W.J., and L. Zhang. 2002. Biochemical and nutrient removal patterns of created riparian wetlands: Eight-year results. In: Mitsch, W.J. and L. Zhang (eds.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 2001. Columbus, OH, pp. 61-68.

Mitsch, W.J. and L. Zhang. 2003. Biogeochemical patterns of created riparian wetlands: Ninth-year results (2002). In: Mitsch, W.J., L. Zhang, and C. Anderson (eds.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 2002. Columbus, OH, pp. 75-80.

Mitsch, W.J., L. Zhang, N. Dillon, and D. Fink. 2004. Biogeochemical patterns of created riparian wetlands: Tenth-year results (2003). In: Mitsch, W.J., L. Zhang, and C. Tuttle (eds.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 2003. Columbus, OH, pp. 59-68.

Mortensen, P. and P. Lanzky. 1996. Water quality improvement in a constructed wetland, Thesis, Royal Danish School of Pharmacy, Copenhagen, Denmark.

Mortensen, P., P. Lanzky, and S.E. Jørgensen, 1997. Nitrogen removal by the Olentangy River experimental wetlands two years after construction. In: Mitsch, W.J.(ed.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1996, Columbus, OH. pp. 113-117.

Nairn, R.W. 1996. Biogeochemistry of newly created riparian wetlands: Evaluation of water quality changes and soil development. Ph.D. dissertation, Environmental Science Graduate Program, The Ohio State University, Columbus, OH.

Nairn, R.W. and W.J. Mitsch. 1997. Water quality changes in newly constructed riparian wetland, 1994-95. In: Mitsch, W.J., (ed.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1996, Columbus, OH. pp. 139-150.

Nairn, R.W. and W.J. Mitsch. 2000. Phosphorus removal in created wetland ponds receiving river overflow. Ecological Engineering 14: 107-126.

Spieles, D. J. 1998. Nutrient retention and macroinvertebrate community structure in constructed wetlands receiving wastewater and river water. Ph.D. dissertation, Environmental Science Graduate Program, The Ohio State University, Columbus, OH.

Spieles, D.J. and W.J. Mitsch, 1998. The effects of season and hydrologic and chemical loading on nitrate retention in constructed wetlands: A comparison of low and high nutrient riverine systems. In: Mitsch, W.J. and V. Bouchard (eds.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1997. Columbus, OH, pp. 105-117.

Spieles, D.J. and W.J. Mitsch. 2000. The effects of season and hydrologic and chemical loading on nitrate retention in constructed wetlands: A comparison of low and high nutrient riverine systems. Ecological Engineering 14: 77-91.

Spieles, D.J. and W.J. Mitsch. 2003. A model of macroinvertebrate trophic structure and oxygen demand in freshwater wetlands. Ecological Modellling 161: 183-194.

U.S. Environmental Protection Agency. 1983. Methods for chemical analysis of water and wastes. 600/4-79-020, U.S. Environmental Protection Agency, Cincinnati, OH.

Vorwerk, N. 1997. Comparison of three years of pH values between planted and unplanted wetlands. Honors thesis, School of Natural Resources, The Ohio State University.

Vorwerk, N. and W.J. Mitsch. 1998. Comparison of three years of pH values between planted and unplanted wetlands. In: Mitsch, W.J. and V. Bouchard (eds.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1997, Columbus, OH. pp. 97-104.

Wehr, A. 1995. Early water quality of created wetlands at the Olentangy River Wetland Research Park. Honors thesis, School of Natural Resources, The Ohio State University.

Wehr, A. and W.J. Mitsch. 1996. Early water quality of created wetlands at the Olentangy River Wetland Research Park. In: Mitsch, W.J.(ed.) Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1995, Columbus, OH. pp. 83-90.